The data in Figure 38 illustrate the very complex impulse timing patterns which were found over bands of frequencies. These patterns can and did change significantly with time of day as the various sources involved were changed, new sources were added, capacitor banks near each source were switched, and other line parameters were changed.

A few exploratory measurements were made at the UTC Gatehouse 3 site at higher frequencies. Figure 39 shows noise at the 39 to 49 MHz frequencies along with a few low band VHF land mobile communications signals. A distinct set of slanting lines across the entire frequency band was spaced at 8.3 ms intervals, suggesting a single phase source operating on both the positive and negative portions of the power line frequency. Amplitude variations of the noise across the 10 MHz wide band of frequencies show the familiar peaks and nulls associated with frequency-sensitive elements.

An even wider frequency band which included that of the previous figure was examined in Figure 40. Impulsive noise over the entire 20 to 120 MHz band is shown as well as numerous radio signals. The high density of radio signals at 88 to 108 MHz was from FM broadcast stations. Television video and sound carrier signal pairs can be seen at about 55 and 62 MHz. Impulsive noise with an 8.3 ms spacing extended across the entire band. Noise and signal amplitudes are shown in the upper view where signal-to-noise values can be easily scaled from the view.

Brief bursts of unusual band-limited impulsive noise were noted around 62.5 MHz at the UTC Gatehouse 3 site. The noise burst can be seen in Figure 42 from 9.5 seconds down to 2 seconds on the time axis scale of the lower view along with the previously observed impulsive noise at 8.3 ms intervals. The burst-related impulses were spaced slightly more than 16.6 ms apart and each impulse had a duration of about 4 ms. These unusual pulses were not quite synchronized with the 60 Hz power line frequency. Over the 7-second duration of the burst, timing with respect to the 60 Hz impulses changed by about 6 ms (or about 130° of phase shift).

The upper view of Figure 41 shows impulses of noise which approach -60 dBm in amplitude. These impulses can be seen in the lower view as random noise signals scattered throughout the view. A second more distinct impulse amplitude level varying around -70 to -75 dBm in amplitude was associated with the 8.3 ms interval impulsive noise. The unusual burst noise amplitude can be seen in the upper view between the two television signals at about -80 dBm.

Another example of the burst noise is shown in Figure 42. At the top of the view the bursts were about 8 ms wide and synchronized with the 60 Hz power line frequency. At about 9 seconds on the time scale the phase of the burst noise with respect to the power line frequency shifted, and the noise pulse width narrowed. The origin of these unusual bursts of noise was not determined, except that the source was believed to be within the UTC plant.

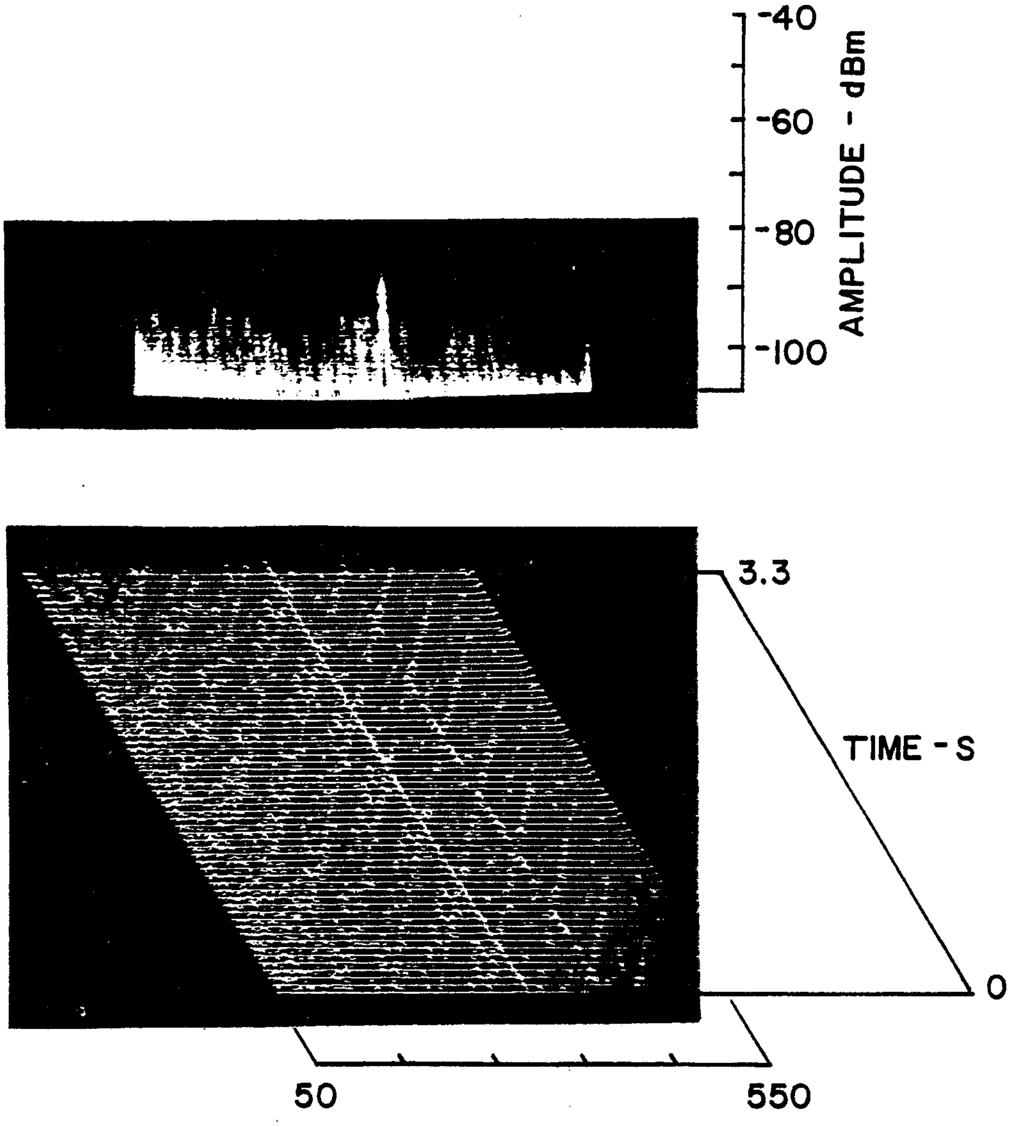

Figure 37 UTC Gatehouse 3 Site, 6/26/78, 1005

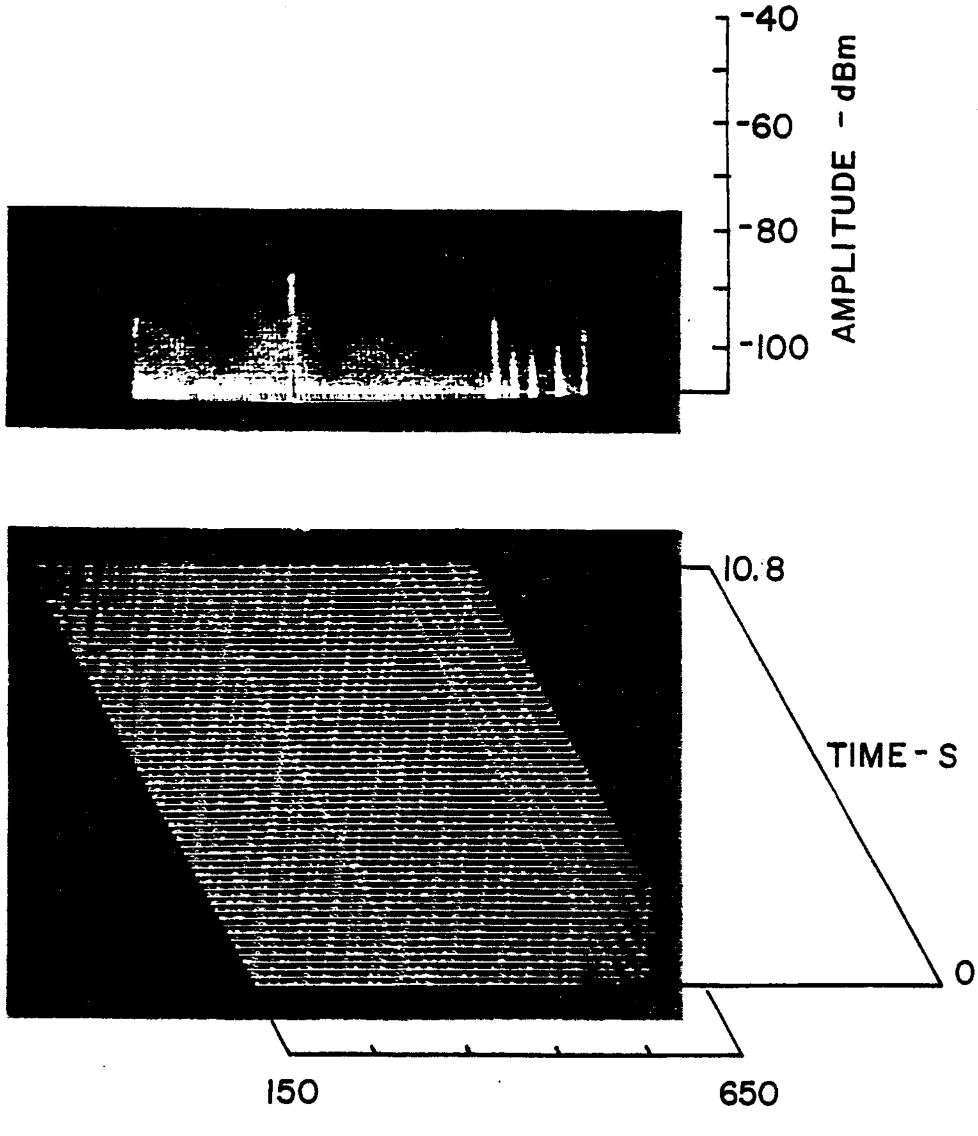

Figure 38 UTC Gatehouse 3 Site, 6/26/78, 1014

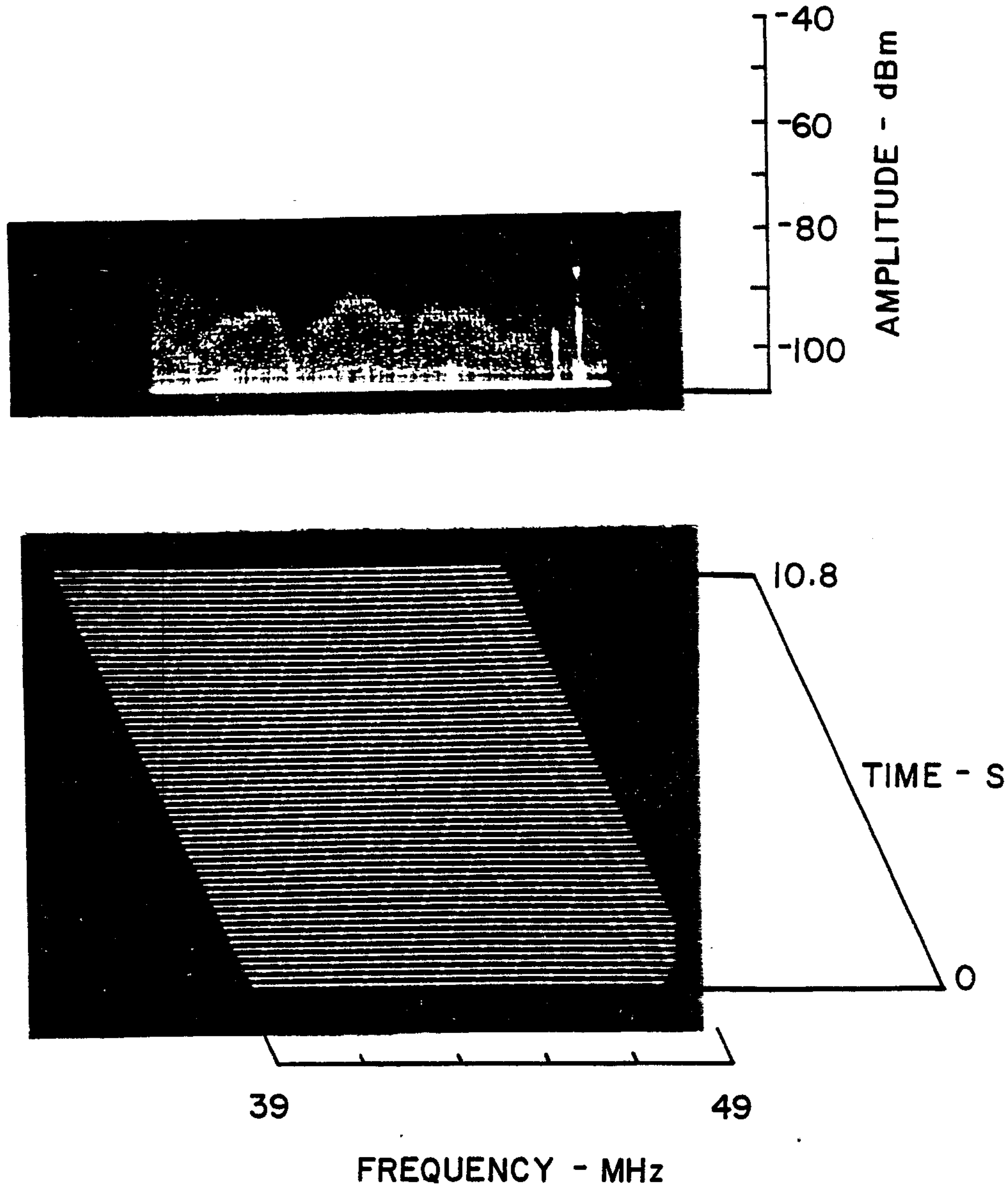

Figure 39   UTC Gatehouse 3 Site, 6/26/78, 1135

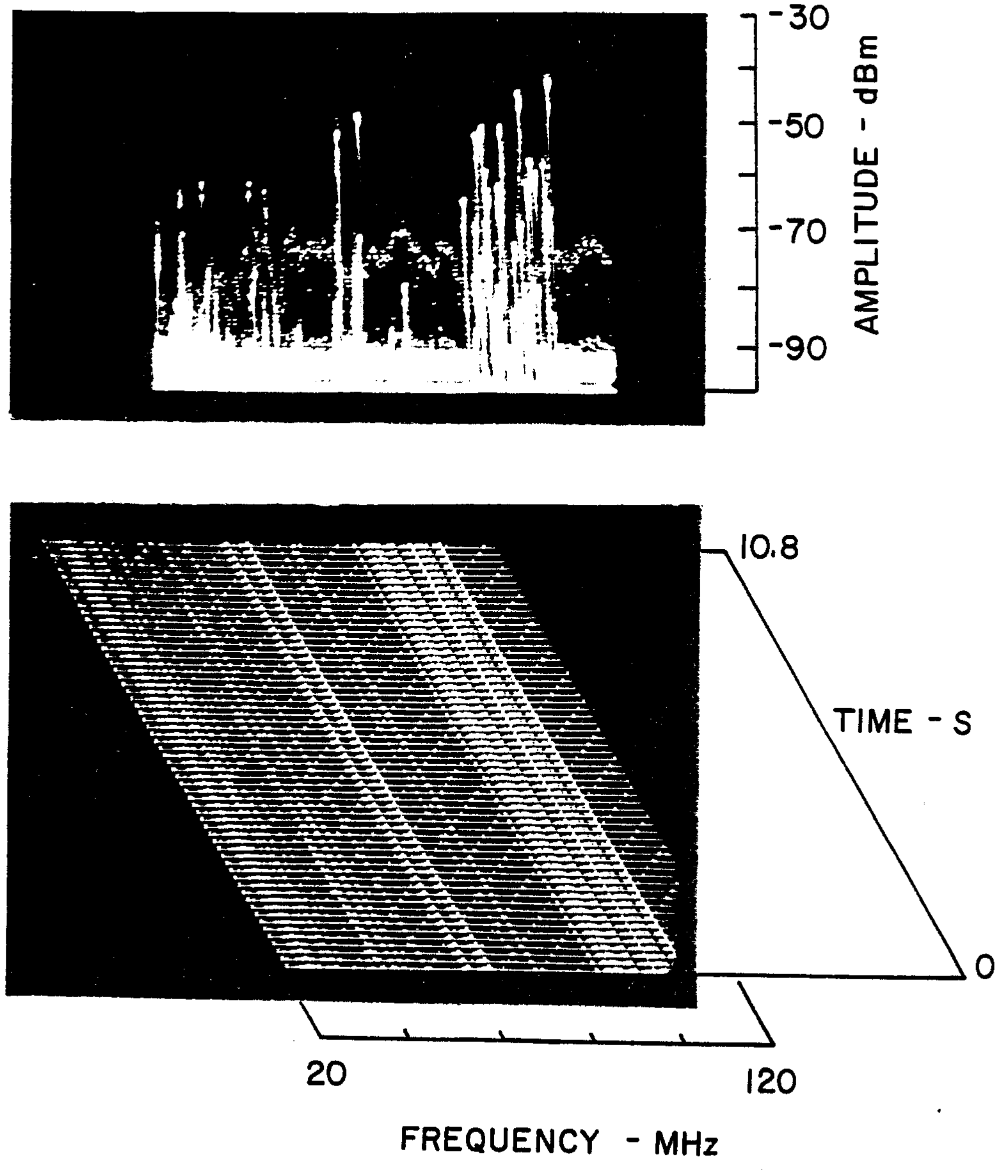

Figure 40   UTC Gatehouse 3 Site, 6/26/78, 1231

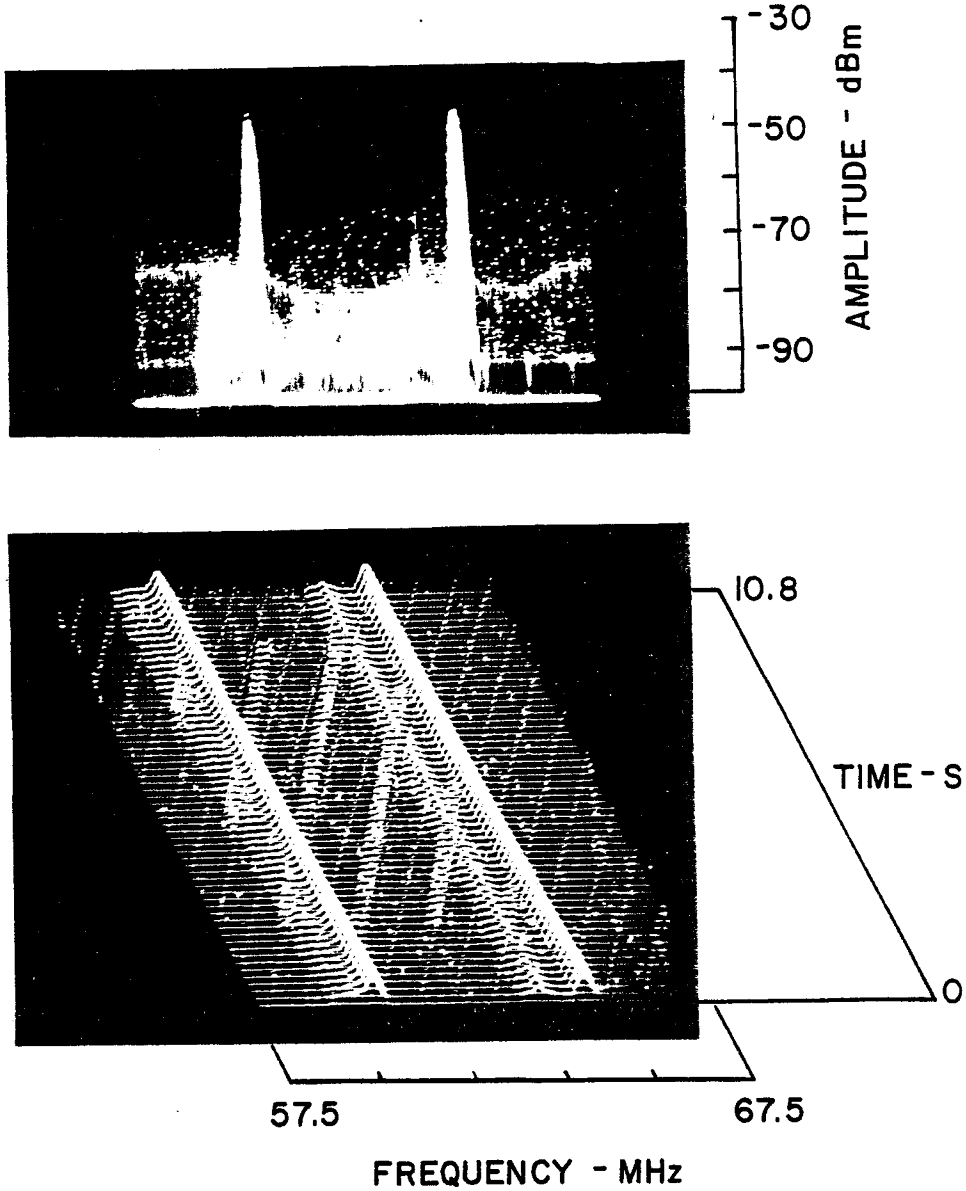

Figure 41 UTC Gatehouse 3 Site, 6/26/78, 1249

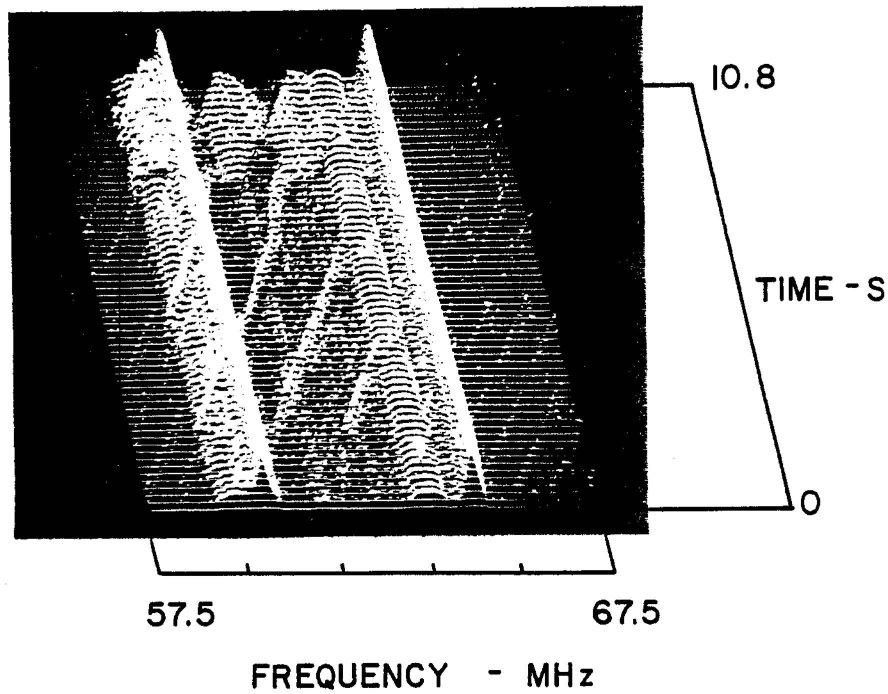

Figure 42 UTC Gatehouse 3 Site, 6/26/78, 1258

Section 4

DISCUSSION

4.1 BACKGROUND NOISE

Electrical noise associated with distribution line insulator and hardware leakage was expected to be a primary source of background noise on the CL&P 13.8 kV distribution line. However, the measurements described in Section 3 did not support this assumption. Instead, an impressive variety of highly impulsive background noise was found to be the primary kind of noise conducted along and emanated from the CL&P distribution lines. The impulses were synchronous with the power line frequency.

Most background noise varied in amplitude with frequency, and frequency-flat noise properties were seldom found. Also, most impulsive noise was at a constant amplitude at any given frequency. Random amplitude impulsive noise was rarely found. This constant amplitude characteristic was different from the more random amplitude variations reported in previous measurements of the amplitude probability distribution (APD) of power line noise [4,5]. However, differences in measurement conditions between these and previous measurements may account for some of the lack of agreement between these and the previous measurements. The variations in amplitude vs. frequency found on most measurements implied that resonant conditions existed in the source-to-sink path of the noise signal. Little data were available on the reactive impedances at the frequencies measured of components used in utility distribution systems.

The source of the impulsive noise was a matter of concern and speculation during the measurements. All available evidence suggested that high power synchronous switching devices employed in industrial process controls were the primary sources. Impulses from these devices apparently propagated from each source backward onto the CL&P distribution lines. This type of impulsive noise has been noted in other measurements of radio noise in urban and suburban areas [6,7].

The noise measurements at Gatehouse 3 verified that several impulse noise sources were operating in the UTC plant. These measurements were made adjacent to the rear of the main facility, and similar noise levels were not found during other more distant measurements. It would have been of high general interest to ascertain the specific sources of each component of the observed noise and relate these sources to background noise found emanating from the CL&P line at the UTC Riser Pole site. However, this type of effort was beyond the scope of the assigned work task.

4.2 CONVERTER NOISE

The distinctive and strong noise levels from the UTC experimental converter bridge measured at the UTC Riser Pole site were directly related to converter operation. The noise started immediately upon converter start-up and went away immediately upon converter shutdown. The band of frequencies containing maximum noise was identified by an iterative trial and error process. Other measurements at lower frequencies and at higher frequencies did not reveal any other peaks similar to those found in the 25 to 75 kHz frequencies. Lower amplitude peaks and nulls probably were present at other frequencies, but time was not available for an extensive search for weak noise components.

Loop orientation was varied during reception of the converter noise. All orientation measurements verified that the noise was radiated from the overhead distribution line. No evidence was noted that suggested direct radiation from the UTC facility to the loop or whip sensors (except for the Gatehouse 3 background measurements where the site was physically very close to the plant).

The electrical circuit from the inverter to the riser pole included internal plant wiring in conduits, large electrical switches, transformers, underground cables, and other electrical power handling devices. Obviously these devices passed significant 25 to 75 kHz impulse power levels from the converter to the riser pole and onto the CL&P distribution line. However, very little was known about the higher frequency electrical properties of the source or the path to the riser pole. Several important questions remain unanswered, such as:

a. What was the spectral shape of the source?

b. Did the source itself contain maximum energy in the 25 to 75 kHz band, or did the source to riser pole circuit act as a bandpass filter?

c. Did distribution line resonant properties affect the spectral shape measured at the riser pole?

d. Did significant standing waves exist on the distribution line?

e. What was the impedance of the distribution line over the 25 to 75 kHz band at the UTC Riser Pole site and at other points along the line?

f. Would different results have been obtained on the CL&P source side of the UTC Riser Pole capacitor?

Converter noise was identified at the Substation Entrance site and the Spring Pond Park site. Converter noise was not found at the Vulcan Radiator or the Feeder 4 sites. These observations raise questions concerning the variable propagation path along the various distribution lines used for measurement. Table 7 provides the distances from the UTC Riser Pole site to each of the other sites. Converter noise amplitude at the various sites can be scaled from the 3-axis views given in Section 3. From these amplitude values and the distances in Table 7 line loss in terms of dB/kft can be established.

Table 7

DISTANCE FROM UTC RISER POLE TO OTHER SITES

Site	Distance in kft
UTC Riser Pole	0.0
Substation Entrance	3.85
Feeder 4	4.31
Vulcan Radiator	7.70
Spring Pond Park	17.05

Converter noise was attenuated about 25 dB from the UTC Riser Pole to the Substation Entrance site or about 6.5 dB/kft. The measurements suggest an attenuation of less than 3 dB for the much longer path between the Substation Entrance and the Spring Pond Park sites, giving a loss of less than 0.2 dB/kft. Converter noise was not observed at either the Feeder 4 or the Vulcan Radiator sites even though the distances were much less than to the Spring Pond Park site. Obviously, simplistic measures of loss based upon measured inductive field levels at each site cannot be used to predict distribution line losses at the frequencies involved.

The observed measurements of inductive field strengths suggest that standing waves were present on the CL&P lines, and that the magnitude of the inductive magnetic field measured by the loop antennas probably provided isolated measurements of the standing wave pattern. The amplitude vs. frequency patterns observed in the converter noise (see Figures 7, 8, and 12) also support the presence of standing waves.

4.3 CAPACITOR EFFECTS

The very distinct changes in the spectral shape of the converter noise (measured at the UTC Riser Pole) when the UTC Riser Pole power factor correction capacitor was switched in or out were unexpected (see Figures 9 through 11). With the UTC Riser Pole Capacitor bank in, the results show that the magnitude of the inductive magnetic field component measured by the loopstick was changed as follows:

a. Attenuated at frequencies below 30 kHz suggesting low values of impulse current on the CL&P line below 30 kHz.

b. Very little change between 30 and 37 kHz.

c. Enhancement at frequencies above 37 kHz suggesting high values of impulse current on the CL&P line above 37 kHz.

The observed results provide direct evidence of large and significant changes in the impedance of the CL&P transmission line below 30 kHz and above 37 kHz at the UTC Riser Pole site when the UTC Riser Pole capacitor bank was switched in or out. Discussions with McGraw-Edison personnel have shown that the 30 to 37 kHz transition frequencies are consistent with the expected characteristic frequency of the capacitor banks involved.

The observed results appear to be inconsistent with simplistic modeling of capacitor effects alone. With the capacitor in, one would anticipate high impulse currents at low frequencies from the low impedance capacitor load. However, the loopstick sensors indicated low line currents at low frequencies when the capacitor bank was in and high line currents at low frequencies with the capacitor bank out. Apparently, the combination of the electrical properties of the converter source, UTC plant wiring, UTC transformer bank, underground cable from the UTC plant to the riser pole, and the CL&P transmission line all combined to produce more complex resonance effects. The observation that background impulsive noise did not change when the capacitor banks were switched in or out also suggested that complex circuit factors were involved at the frequencies examined.

The observations suggested that many aspects of the generation and propagation of impulsive noise over the system measured were poorly understood. A number of questions were formulated during the evaluation of the data. Some of these questions were:

a. What were the electrical properties of the 1200 kVAR capacitor at the UTC Riser Pole site over the 20 to 100 kHz frequencies?

b. What were the electrical properties of the distribution line at the UTC Riser Pole site over the 20 to 100 kHz frequencies?

c. Were the resonance effects noted primarily due to capacitor internal properties or were they due to the capacitor in conjunction with other distribution line components such as transformers, line lengths, loads, or source?

d. Would a 600 kVAR capacitor or a capacitor by another manufacturer produce similar results?

e. Would similar results have been observed on the CL&P source side of the capacitor?

Answers to the above questions can be obtained with additional investigative efforts. However, the additional work required was well beyond the scope of the limited program undertaken by McGraw-Edison and SCI.

4.4 IMPLICATIONS TO POWER CARRIER COMMUNICATIONS

A few operational power carrier communications systems and a number of experimental systems are now operating on utility distribution lines. These systems are employed for various control and telemetry purposes including functions such as switching, load control, status reporting, meter reading, and similar operations. Large expansions in these systems are currently being considered to reduce the cost of day-to-day operation of utilities. These expansions will be implemented to meet communications requirements as soon as communications system costs and performance reach reasonable levels.

Power carrier communications systems operate at the 5 to 500 kHz frequencies explored in these measurements. The impulsive noise levels measured at the various sites are the noise levels which will limit the performance of power carrier communications systems. A review of the available literature on noise levels limiting the performance of power carrier communications employed on distribution lines did not reveal significant or comparable data except for similar measurements in other cities [3,4].

The measurements suggest that significant levels of impulsive noise synchronous with the power line frequency will be experienced on many distribution lines in urban and suburban areas. Furthermore, the noise will vary (1) as sources are turned on and off, (2) with time of day, (3) as power factor correction capacitors are switched, (4) from distribution line to distribution line, (5) along a given distribution line, and (6) perhaps with other unknown factors. The measurements imply that attenuation/mile values of current or voltage often used in system design may not be realistic for field practice, and unusually low or unusually high values of attenuation/mile may be obtained for similar lines. The data suggest that standing waves exist along the distribution lines which must be considered in systems design and the standing wave patterns can be changed by discrete power line components such as capacitors and loads. Furthermore, the urban and suburban areas where carrier communications systems are most urgently needed are the areas with the highest population of impulsive noise sources.

These factors suggest that widespread use of power carrier communications on distribution lines will not be successfully implemented until noise control procedures are implemented, systems highly immune to a complex variety of impulsive noise conditions are developed, and systems capable of adjusting to complex impedance changes are devised. Consistent performance from installation to installation requires that both noise levels and propagation along the distribution line be better understood.

4.5 TERMINOLOGY

The term "impulsive noise" has been used throughout this report to describe the brief and short duration impulses that were found to be the predominant type of noise emanating from CL&P transmission lines. The term can also be physically related to the switching transients created by the source devices. Most observed noise impulses were synchronized to the utility line frequency because of the operation of the source devices. These repetitive pulses of constant period can be analyzed for spectral content by conventional Fourier transform processes, or the fine grain spectral analysis of these sequences of pulses can be measured with modern spectrum analyzers based on Fast Fourier Transform (FFT) techniques. Such analyses or measurements would show that harmonic spectral components spaced at 60 and 120 Hz would be present throughout the frequency bands examined for 1Ø related sources, and by 180 and 360 Hz for 3Ø related sources. Cummins [3] has examined the fine scale structure of noise emanating from power lines by translating a small 4 kHz wide band of frequencies near 20 MHz downward to 0 to 4 kHz. The translation process was accomplished with a stable HF receiver operating in a linear mode without automatic gain control. The 0 to 4 kHz translated band of frequencies was then examined by an FFT instrument. Distinct harmonic structure was identified with 60 and 120 Hz components. These high frequency harmonic components were an extension of the lower frequency and conventional power line harmonics measured by McGraw-Edison. In many respects the high frequency spectral components could be considered to be power line harmonics, or perhaps more properly as harmonics of the power line frequency.

The term "power line harmonics" seems to be somewhat misleading for the observed noise. The 3 kHz to 100 MHz impulsive energy did not originate from standard utility system components. Nor did most of the more conventional harmonic components measured by McGraw-Edison originate from CL&P. The harmonics originated from other customer-related sources which fed impulsive energy back into the CL&P system. The CL&P transmission lines carried these impulses along with electrical power at 60 Hz. The term "impulsive noise" has been used to provide a means to distinguish this newer set of signals from conventional power line harmonics which historically have been related to wave shape distortion from power system generation and distribution systems.

The type of spectrum analyzer used in the measurements described in this report was not capable of resolving the 60 and 120 Hz spaced spectral lines at these higher frequencies. The scanning spectrum analyzer employed did provide the magnitude of these components vs. frequency. Thus, no significant data was lost, and significant advantages were obtained with the ability to scan across large blocks of frequencies, tune to any desired center frequency, and examine time domain structure.

Section 5

CONCLUSIONS

The exploratory measurements of electrical noise on CL&P distribution lines from general background sources and from the UTC experimental 1 MW converter bridge were successfully concluded. The primary properties of background noise and converter noise conducted along and emanated from CL&P lines were defined. The measurements also raised significant questions concerning the electrical characteristics of the path from the source to measurement location at frequencies immediately above conventional harmonic frequencies upward to about 500 kHz.

The instrumentation technique employed for the measurements proved to be highly effective in defining the broadband spectral properties of noise as well as time domain characteristics. Non-flat noise properties were predominant. Most noise was impulsive with predominant amplitude levels rather than being random in amplitude. Most impulses were synchronous with the 60 Hz power line frequency.

The primary source of impulsive background noise was believed to be high power switching devices employed by CL&P customers for industrial process controls. These sources were dispersed along the distribution lines examined. The UTC facility contained a number of impulsive noise sources as well as the experimental converter bridge source. Impulses from these switching devices and from the converter propagated back through plant wiring and onto the CL&P distribution lines.

The converter-generated impulsive noise results described in this report were obtained with an experimental converter bridge available at the UTC Power Systems Division. This particular bridge did not contain shielding and filtering that would probably be incorporated in equipment designed for delivery to customers. Thus, the results presented in this report may be a worst case situation. However, the results suggest that minimal cost converters without appropriate shielding and filtering should not be employed on a large scale basis throughout the utilities industry.

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SCii
SYSTEMS CONTROL, INC. ■ 1801 PAGE MILL ROAD ■ PALO ALTO, CA 94304 ■ TELEX 348-433 ■ (415) 494-1165

Technical Report No. 4068-150679 June 1979

ELECTRICAL NOISE IN THE 3 TO 300 kHz BAND ON ELECTRIC UTILITY DISTRIBUTION LINES FROM A TRANSIT SYSTEM RECTIFIER

Prepared for:

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P.O. Box 440
Canonsburg, Pennsylvania 15317

Under:

Electric Power Research Institute
Contract RP 1024-1

Prepared by:
W.R. Vincent

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Section 1

INTRODUCTION

Under EPRI Contract RP1024-1, the Power Systems Division of the McGraw-Edison Company, Canonsburg, Pennsylvania, was tasked with the measurement of harmonic voltage and current levels on Potomac Electric and Power Company (PEPCO) distribution lines. The lines were connected to the Tuxedo substation 13.8 kV bus supplying electrical power to a rectifier bridge for d.c. traction power to a section of the Washington Metropolitan Area Transit Authority (WMATA) train tracks. McGraw-Edison subcontracted with Systems Control, Inc. (SCI) of Palo Alto, California, to measure electrical noise levels on the PEPCO distribution lines at frequencies higher than conventional harmonic frequencies. The SCI measurements were made primarily at frequencies commonly called very low frequencies (VLF) covering the 3 to 30 kHz range and the low frequencies (LF) covering the 30 to 300 kHz range. A few exploratory measurements were made above and below the VLF and LF bands in order to provide a comprehensive understanding of observed noise properties.

The SCI VLF and LF measurements were conducted simultaneously with the harmonic measurements of McGraw-Edison. These measurements complemented and supplemented the McGraw-Edison harmonic measurements by extending the frequency range upward and by the use of additional instrumentation to define noise properties.*

The measurements described in this report were, to a large extent, exploratory in nature. A literature search did not reveal significant data which directly applied to the PEPCO/WMATA type of situation. Thus, it was necessary to adopt an iterative measurements procedure where measurement system parameters were adjusted as experience was gained throughout the measurements period. Both McGraw-Edison and SCI field

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* The term impulsive noise has been used in this report because it can be physically related to primary properties of the observed noise. The relationship between the term "impulsive noise" and "higher order power line harmonics" or "higher order harmonics of the power line frequency" is discussed in Section 4.5.

measurement personnel realized that a significant opportunity existed to relate a specific and controlled source of harmonic and noise energy to harmonic and noise levels on the associated distribution lines. An excellent working arrangement rapidly developed between the various parties involved in the effort, including PEPCO, WMATA, McGraw-Edison, and SCI personnel, which permitted the investigation to be accomplished efficiently and with reasonable depth.

Section 2

INSTRUMENTATION

Instrumentation used to acquire data presented in this report was adapted from equipment used for previous field measurements where little was known about the frequency or time domain properties of signals or noise [1-3]. A frequency scanning receiver was employed to observe noise amplitude across large blocks of frequencies where the scanning process was also employed to aid in defining the time domain structure of the wideband noise under observation. Figure 1 shows a block diagram of the primary instrumentation components.

Simple whip or loop antennas were employed for most measurements to sense the electric or the magnetic component of the field around the transmission line caused by impulse voltage and current on the line. The antennas were placed directly under the transmission line in the inductive or near field region. In addition, the instrumentation was occasionally connected directly to voltage probes and current sensors attached to the distribution line by McGraw-Edison for harmonic measurements.

A Hewlett-Packard 140 Spectrum Analyzer was employed as a scanning receiver to drive an EMTEL Model 7200B 3-Axis Display. The 3-axis display provided a moving real-time visual representation of noise received by the scanning receiver.

To acquire data the spectrum analyzer was adjusted to scan across a desired block of frequencies. As the spectrum analyzer scanned through a block of frequencies, its output was divided by the 3-axis display into 512 equally spaced data points. The received signal or noise amplitude at each data point was represented by an 8-bit digital word which provided an amplitude resolution of 256 levels for each data point. When a scan was completed, the 512 amplitude words were stored in memory and then presented as line 1 on the display CRT. When the

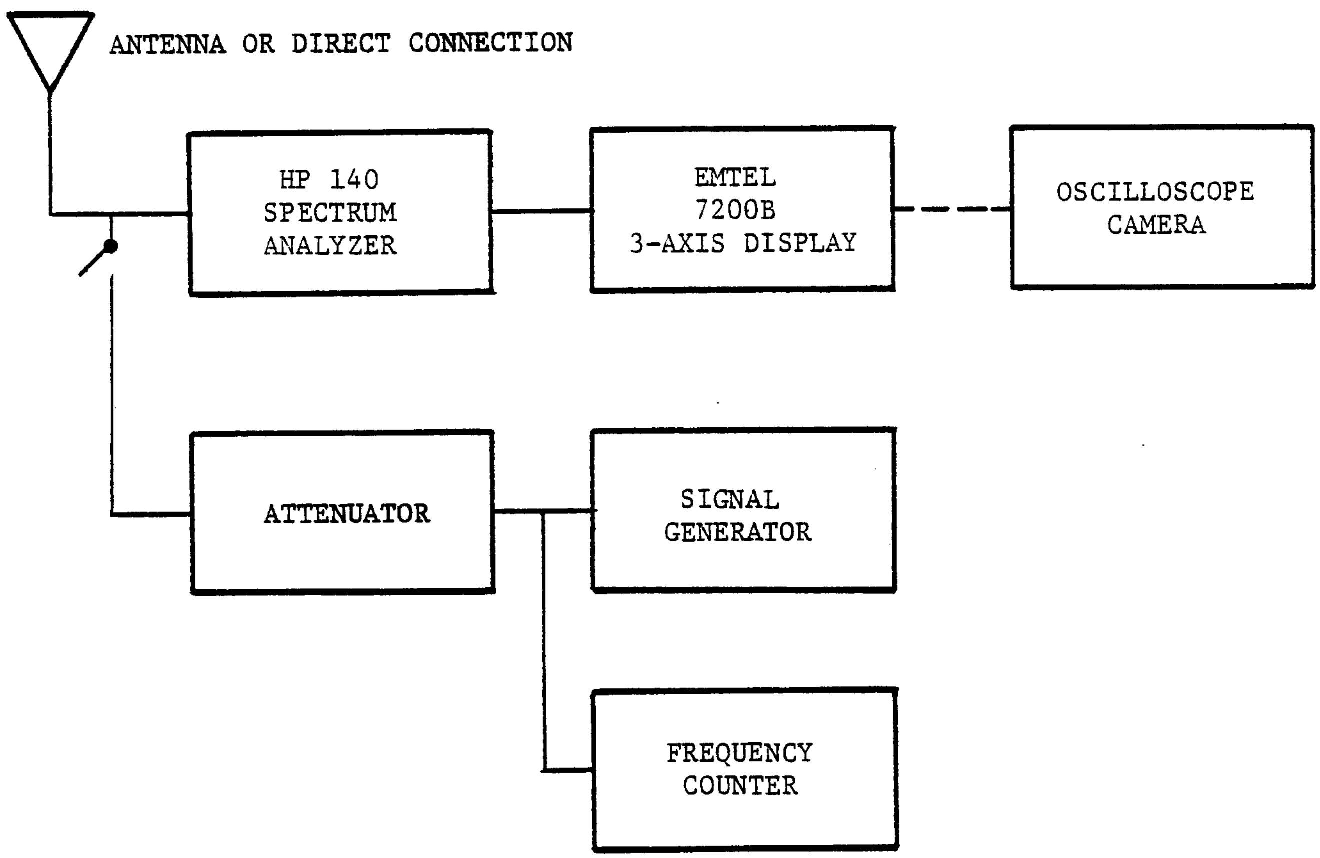

Figure 1 Block Diagram of Primary Instrumentation Components

second scan was completed, its data were stored in memory, line 1 on the CRT moved to line 2, and the new scan was shown on line 1. Subsequent scans moved the earlier data lines step by step along the time axis until the entire memory was filled and a total of 60 scan lines were presented in the 3-axis view. When the memory was full, each new scan caused the oldest scan to be discarded. The resulting animated moving view of signals and noise provided a unique and easy-to-interpret visual picture of noise and signals in the blocks of frequencies under observation.

The 3-axis display system has a number of controls to assist the operator in interpreting the signals. Among these controls are a stop-action control to freeze any desired view for detailed observation, geometry controls to vary the viewing aspect, display mode controls to select any segment of the total view for detailed examination, and a threshold control to vary the background noise level.

The 3-axis views presented in this report were obtained by photographing the display in its stop-action mode. In interpreting the data, consideration must be given to situations where repetitive impulsive signals are observed by the repetitive scanning process. The relative repetition rates of impulsive signals and the scan rate of the receiver produce distinctive bands that slant across the CRT.

The instrumentation was installed in a small self-contained van for mobility and convenience in travel from site to site. Usually, electrical power was provided by PEPCO personnel. When power was not available a small gasoline-powered generator was used to operate the instrumentation.

Section 3

MEASUREMENTS

3.1 GENERAL APPROACH

Prior to the data collection period of 10/24/78 through 12/27/78, McGraw-Edison, PEPCO, and WMATA personnel conducted a survey of the facilities and 13.8 kV distribution lines which might be subjected to harmonic levels from the WMATA rectifiers. Tentative measurement sites were selected during these early surveys which proved to be excellent sites for the measurement and data collection program described in this report. Additional auxiliary sites were visited as time permitted to obtain data at other locations in the PEPCO and WMATA systems.

Instrumentation for the McGraw-Edison harmonic measurements was installed in a small van similar to the SCI van used for the collection of higher frequency data. The two vans, PEPCO line crews and supervisory staff, and WMATA representatives moved to the appropriate site, operated the instrumentation, and then moved to the next site. PEPCO and WMATA personnel provided communications as required to coordinate METRO train movements and power system parameters. The WMATA provided and operated an eight-car train on a completed but unopened section of tracks to produce realistic loads on the rectifier.

Polaroid photographs of pertinent 3-axis display presentations were made to record the noise and signal structure for each test condition. Many of the Polaroid photographs taken in the measurements were selected for presentation in this report. Usually a pair of photographs at two separate viewing aspects was made to better portray all important properties of the observed noise. The versatility of the display in presenting the observed data in viewing aspects which maximized the visual perception of important structures was found to be very useful.

All 3-axis views were accurately calibrated in frequency, amplitude, and time. The frequency and time scales are obvious, except that the horizontal frequency axis in all views is also associated with scan time. A bandpass filter, the scanning receiver IF bandwidth, was moved across the frequency axis from minimum frequency to maximum frequency at a scan time greater than several complete cyles of the 60 Hz power line frequency. Thus, several repetitive and sequential impulses associated with the power line frequency appeared on each scan. This combined frequency and scan time property of the instrumentation was found to be highly useful in the data analysis. All instrumentation operating parameters employed to obtain each view have been provided in convenient tabular form to aid in the scaling of the 3-axis views by interested readers.

Signal amplitude has been expressed in terms of dB below 1 milliwatt at the spectrum analyzer 50 ohm impedance input in all 3-axis views. For those views employing the 108" whip antenna, the dBm scale can be converted into an equivalent field strength in volts/meter by the following conversion:

$$p_n = f_a(k\ T_o\ b)$$

where p_n = mean noise power in watts

f_a = effective antenna noise factor

k = Boltzman's constant τ $1.38 \cdot 10^{-23}$ Joules/°K

T_o = reference temperature (288°K)

b = receiver noise power bandwidth in Hz

T_a = effective antenna temperature in the presence of external noise.

The above expression for p_n can be reduced to:

$$P_n = F_a + B - 204 \quad \text{dBw}$$

which is the power available from the terminals of an equivalent lossless antenna where

P_n = available noise power in dBw

$F_a = 10 \log f_a$, the effective antenna noise figure

$B = 10 \log b$.

The corresponding rms field strength measured by the 108" whip antenna (length << λ) is given by:

$$E_n = F_a + 20 \log f + B - 95.5 \quad \text{dB}(1\mu\text{V/m})$$

where E_n = rms field strength for the bandwidth b

f = frequency in MHz

$B = 10 \log b$.

The amplitude scales for the 3-axis views in this report can be recalibrated in terms of either P_n or E_n from the above relationships and from data contained in the tables of system parameters provided with the views.

3.2 SYSTEM DESCRIPTION

A diagram showing the primary features of pertinent feeder circuits and the dedicated feeder cable serving the WMATA rectifier load is shown in Figure 2. The PEPCO Tuxedo substation serviced a total of 15 feeders, but the secondary bus was split to isolate the particular feeder circuits of interest and to reduce the complexity of the measurements program. The diagram shows all distribution lines involved in the measurement, the measurement sites, and distances between primary features. Figure 2 was taken from the McGraw-Edison master report which describes the related measurements of harmonic voltage and current levels. The McGraw-Edison master report contains more detailed information on the PEPCO distribution system, photographs of each site, and other pertinent data. Sufficient data were taken from the master report to provide a consistent and self-contained document describing the noise results. All site names, PEPCO system names, and WMATA system descriptions are consistent with those used in the master report to simplify the correlation of results between the two measurements.

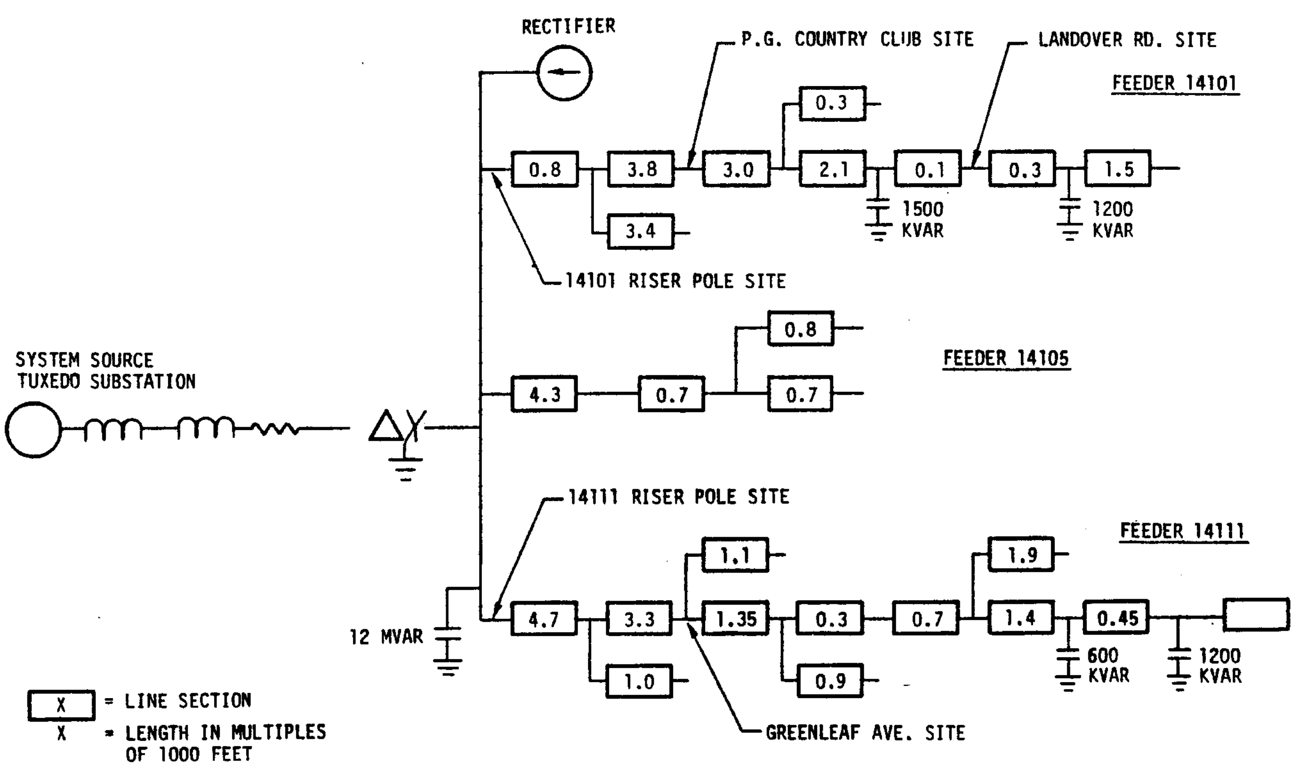

Figure 2 PEPCO System Diagram

3.3 RISER POLE 14111 SITE

3.3.1 Measurement Conditions

Riser Pole 14111 was selected for the first set of measurements because of its close proximity to the PEPCO Tuxedo substation and the feeder cable serving the WMATA rectifier load.

The measurement van was placed directly under the 13.8 kV distribution line identified as Feeder 14111. The line included the Greenleaf Avenue site which was 8,000' from the riser pole. Loopstick and whip antennas were employed to sense electric and magnetic fields from higher frequency noise and signals conducted along the line.

A log of the various actions taken during the Riser Pole 14111 site measurements are given in Table 1. This log provides a convenient reference to the sequence of operations and the status of the PEPCO and WMATA systems. All data on system performance measurements provided in subsequent paragraphs can be related to this log.

Measurement system parameters for the various 3-axis views taken at the Riser Pole 14111 site are summarized in Table 2. These parameters will be useful to those individuals who wish to scale the 3-axis views for some specific detail. The 3-axis views of WMATA/PEPCO systems measurements can be related to Tables 1 and 2 by date and time of day or with the figure number provided in each table.

Data was taken at the Riser Pole 14111 site on 10/24/78 from about 0930 to 1500 hours local time.

Table 1

RISER POLE 14111 SITE ACTIVITY

McGRAW-EDISON ITEM NO.	LOCAL TIME	DATE	CAPACITOR BANK STATUS	TRAIN STATUS	3-AXIS FIGURE NUMBER
1	1300	10/24/78	All Out	Test Run	—
2	1323	10/24/78	All Out	Train Run	—
3	1345	10/24/78	600 kVAR Cap. Bank on Feeder 14111 at Kenilworth and Frolick Switched In	Off	9
4	1350	10/24/78	600 kVAR Cap. Bank In	Train Run	—
5	1417	10/24/78	Tuxedo Substation 12 MVAR Cap. Bank Switched In	Off	10
6	1421	10/24/78	12 MVAR Cap. Bank In	Train Run	—
7	1435	10/24/78	1200 kVAR Cap. Bank on Feeder 14111 Switched In	Off	—
8	1440	10/24/78	1200 kVAR Cap. Bank In	Train Run	—

Table 2

MEASUREMENT SYSTEM PARAMETERS, RISER POLE 14111

3-AXIS FIGURE NUMBER	DATE	LOCAL TIME	ANTENNA TYPE	LOOP FREQ. kHz	CENTER FREQUENCY	FREQ. WIDTH kHz	IF BAND-WIDTH kHz	SCAN TIME ms	IF REF dB	RF REF dB	TYPE OF DATA
3	10/24/78	1018	Loop	10-40 T35	25 kHz	50	1.0	100	-10	0	Background
4	10/24/78	1050	Loop	40-150 T100	100 kHz	100	1.0	100	-30	0	Background
5	10/24/78	1059	Loop	40-150 T100	135 kHz	20	0.3	100	-40	0	Background
6	10/24/78	1236	Loop	150-450 T500	500 kHz	1000	3.0	100	-30	0	Background
7	10/24/78	1331	Loop	1600-5000 T1750	1750 kHz	500	3.0	20	-30	0	Background
8	10/24/78	0953	Whip	—	30 MHz	100	1.0	100	-32	0	Background
9	10/24/78	1345	Loop	40-150 T50	50 kHz	50	1.0	100	-30	0	System
10	10/24/78	1418	Loop	40-150 T45	35 kHz	50	1.0	100	-10	0	System

3.3.2 Ambient Measurements

The background noise levels on Feeder 14111 at its riser pole were examined prior to WMATA train measurements. The rectifier load was idled across the PEPCO source without a train load during the background noise level measurements.

Significant background noise was found emanating from Feeder 14111 in the vicinity of the riser pole. Examples are given in Figures 3 through 8. Noise levels in the 5 to 50 kHz band were explored in Figure 3. Very low noise levels were found at the 5 to 20 kHz frequency portion of the view. However, at the 20 to 50 kHz frequencies impulsive noise was found with a complex time structure. The predominant period was 5.3 ms, but additional substructure was found in portions of the band. The amplitude approached -50 dBm near 40 kHz as noted in the upper view.

Background noise in the 50 to 150 kHz band was examined as shown in Figure 4. Again the time domain structure was complex and contained primary components at intervals of both 5.3 ms and 8.3 ms. The peculiar v-shaped noise components seen throughout the lower view implied that an impulsive source was present whose time base varied with the 60 Hz power line voltage amplitude. Noise amplitude vs. frequency shown in the upper view of Figure 4 contained peaks and nulls typical of circuit resonance conditions at the noise source, between the source and the measurement site, or on the distribution line.

Four distinct continuous wave signals can be seen in the 130 to 150 kHz portion of the 3-axis views of Figure 4. These were found to be power carrier communications signals associated with nearby PEPCO transmission lines. Some leakage of power carrier communications into Feeder 14111 was identified by varying loop orientation.

Background noise and power carrier communications signals in the 125 to 145 kHz band are shown in Figure 5. The impulsive noise fell below the display threshold setting at about 130 kHz. Power carrier communications signals were found at 133, 135, 137, 142, and 147 kHz at amplitude levels shown in the upper view. Figure 5 provides an expanded view of the power carrier signals shown in the upper frequency portion of the previous set of 3-axis views (Figure 4).

Noise emanating from Feeder 14111 over the 0 to 1000 kHz range is shown in Figure 6. Noise at the lower frequencies as well as the power carrier communications signals shown in the previous views was compressed into the left edge of Figure 6. From about 130 to 250 kHz the noise levels were very low. At 250 to 1000 kHz impulsive noise reappeared. The time domain structure was again complex as shown in the lower view. Peaks and nulls typical of resonant conditions in the noise source-to-measurement circuit are shown in the upper view.

In Figure 7 the time spread or time diffuse detail of a form of impulsive noise was defined by employing a receiver scan time of 20 ms. The noise impulses started and terminated at precise times where the interval from the start of an impulse to the start of the next impulse was 8.3 ms. The 8.3 ms period suggested a single phase source which triggered on both the positive and negative cycles of the power line frequency. The 6 ms duration of each noise burst suggested that the noise lasted for about 75% of each half-cycle of the single phase source. The noise was band-limited to a frequency range of 1.5 to 1.85 MHz. While the sharp start and termination of the noise suggested some form of man-made device, the actual source was not identified other than as a signal emanating from Feeder 14111.

In Figure 8 a well-defined time spread or time diffuse noise was observed which had a period of 16.6 ms (see top of view). The 16.6 ms period suggested a single phase source which triggered on either the positive or negative half of the power line frequency. At about 7 seconds on the time scale a second noise component appeared in between the 16.6 ms spaced impulses. The 8.3 ms spacing suggested either two separate sources or one source that somehow added a switching time on the opposite polarity of the line voltage. The very limited frequency range of the scan was too narrow to define band-limiting properties of the noise.

3.3.3 System Measurements

Measurements were undertaken at Riser Pole 14111 to search for rectifier noise as WMATA trains were operated. Four separate train runs were examined for various capacitor configurations as follows:

Run 1 - All capacitor banks out

Run 2 - 600 kVAR capacitor bank at Kenilworth and Frolick in

Run 3 - 12 MVAR capacitor bank at Tuxedo substation in

Run 4 - 1200 kVAR capacitor bank on Feeder 14111 in

Rectifier noise from WMATA train operation was not identified in the 3-axis views taken at Riser Pole 14111. Background noise was measured which was in general agreement with the examples in Figures 3 through 8.

Measurements were also taken as the capacitors were switched. Two examples are shown in Figures 9 and 10. In Figure 9 the 600 kVAR capacitor bank at Kenilworth and Frolick on Feeder 14111 was switched from out to in at the time shown in the 3-axis view. No change in background noise was noted at the capacitor switch time. Switching transients were not observed.

In Figure 10 the Tuxedo substation 12 MVAR capacitor bank was switched from out to in at the time shown in the 3-axis view. Again, background noise changes were not observed, and switching transients were not found.

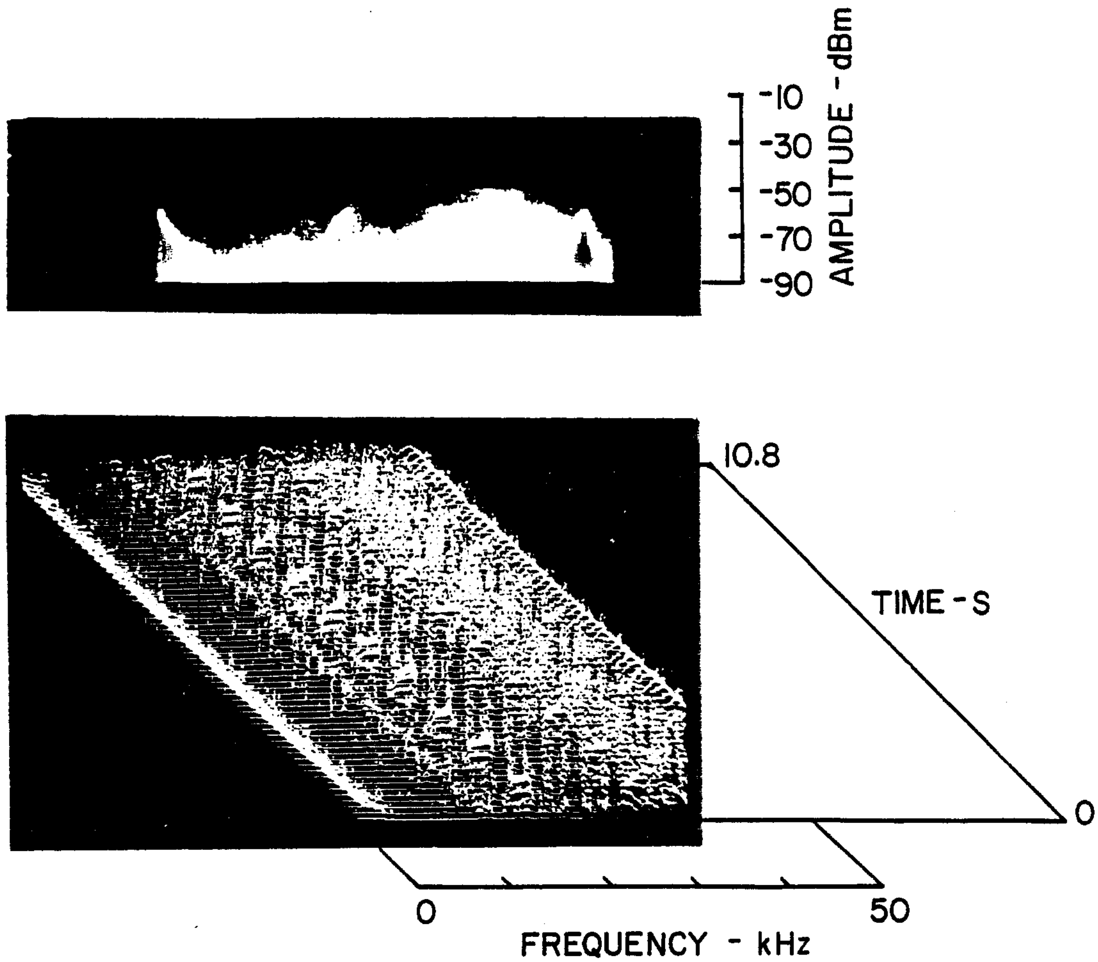

Figure 3   Riser Pole 14111 Site, 10/24/78, 1018

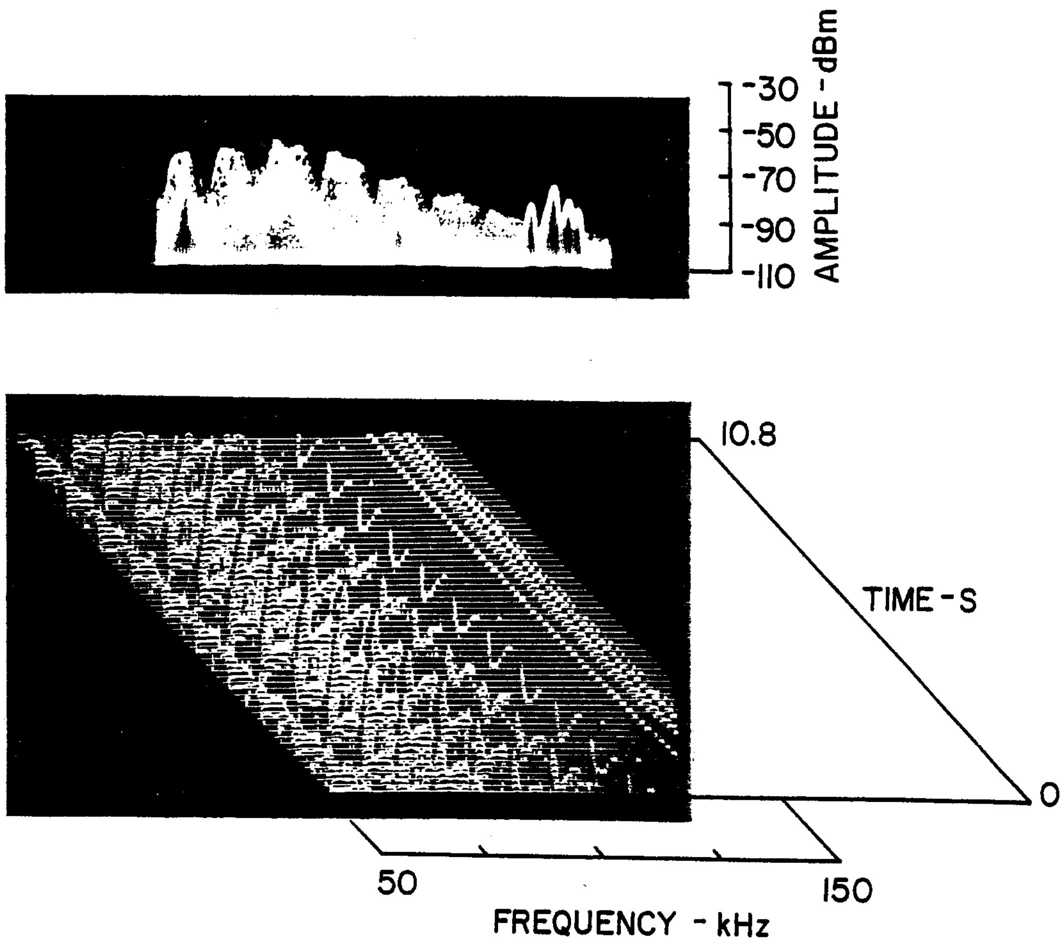

Figure 4 Riser Pole 14111 Site, 10/24/78, 1050

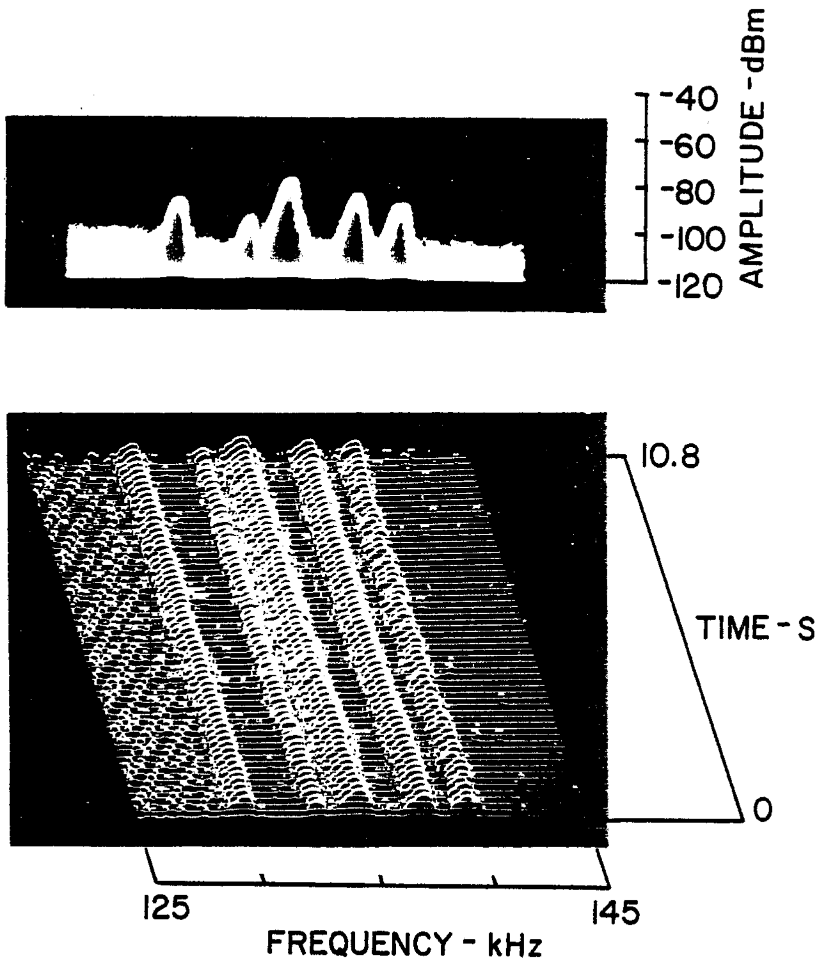

Figure 5 Riser Pole 14111 Site, 10/24/78, 1059

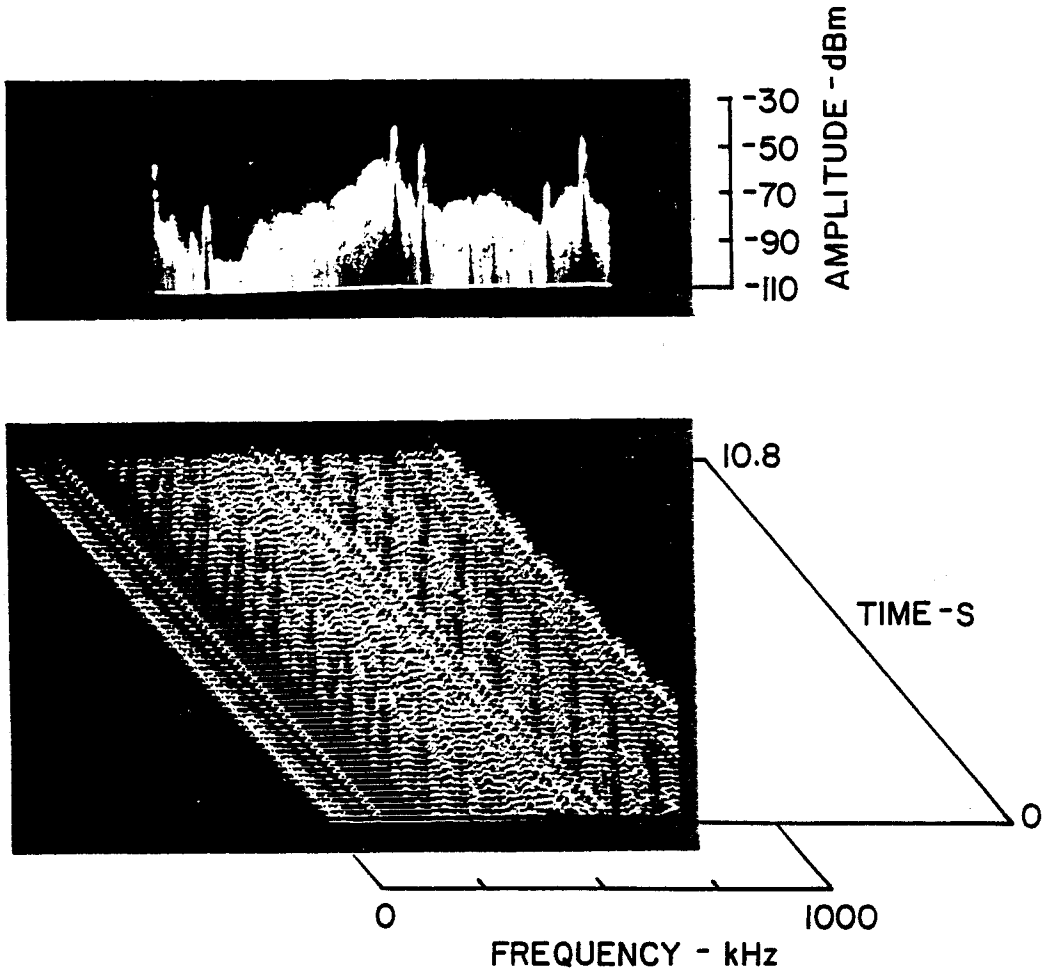

Figure 6 Riser Pole 14111 Site, 10/24/78, 1236

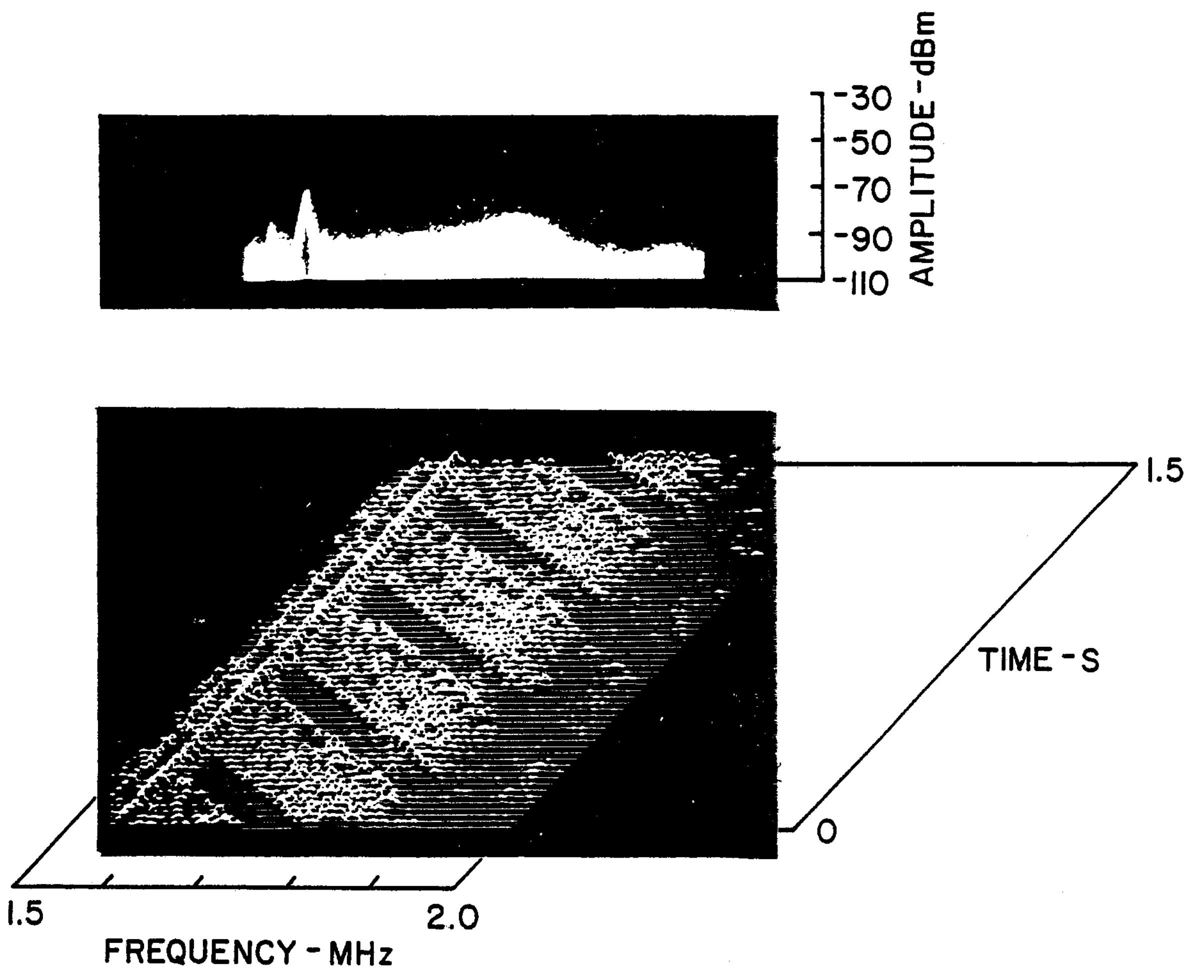

Figure 7 Riser Pole 14111 Site, 10/24/78, 1331

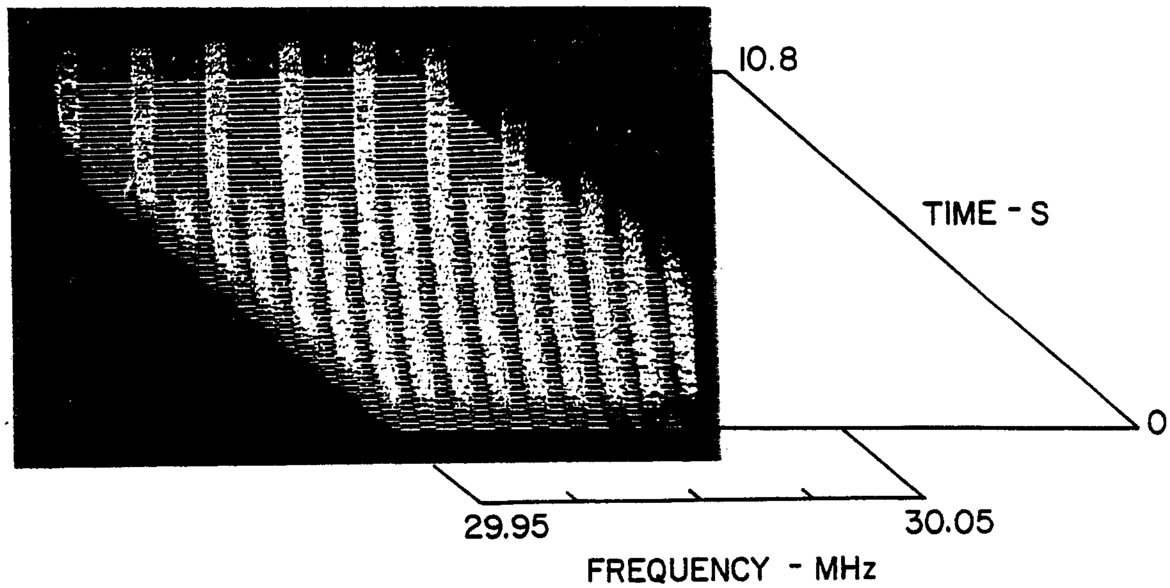

Figure 8 Riser Pole 14111 Site, 10/24/78, 0953

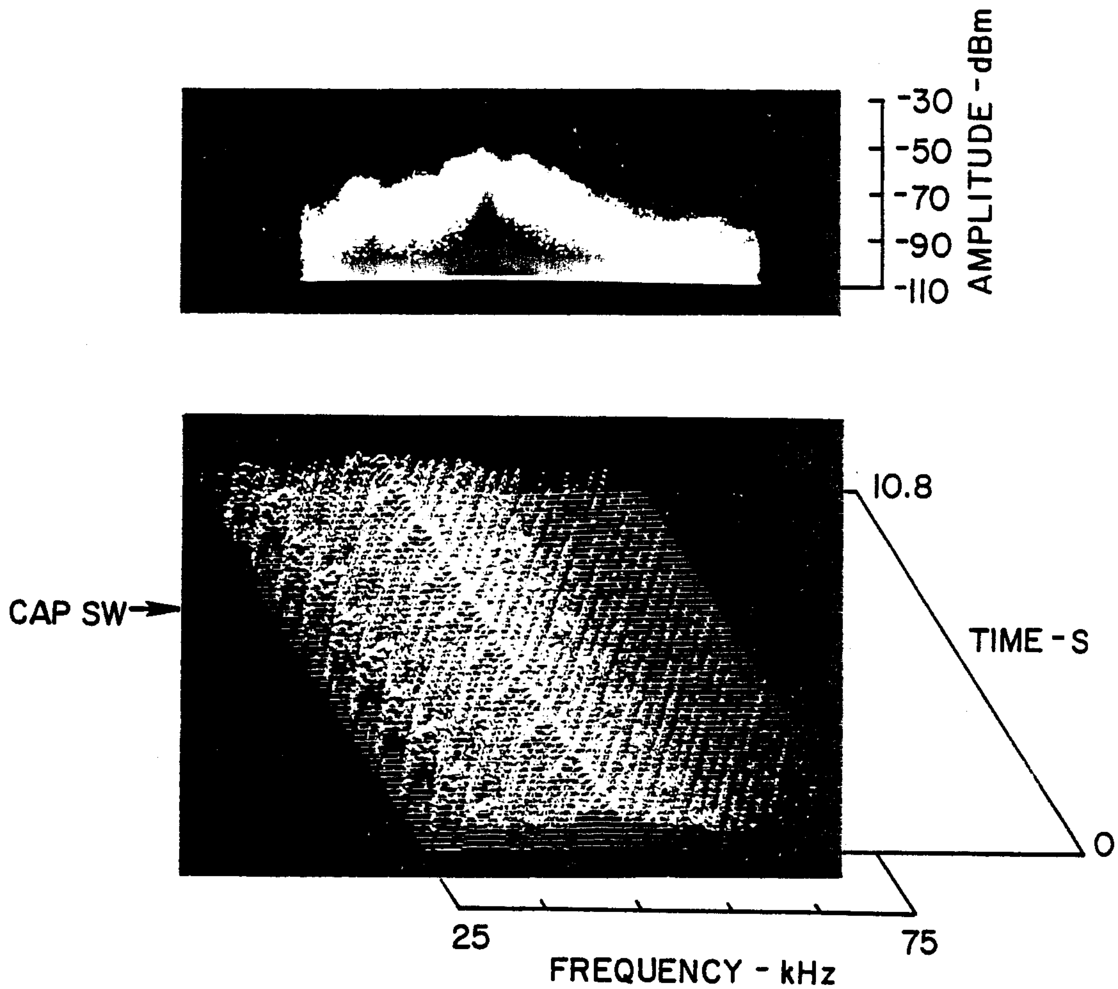

Figure 9 Riser Pole 14111 Site, 10/24/78, 1345

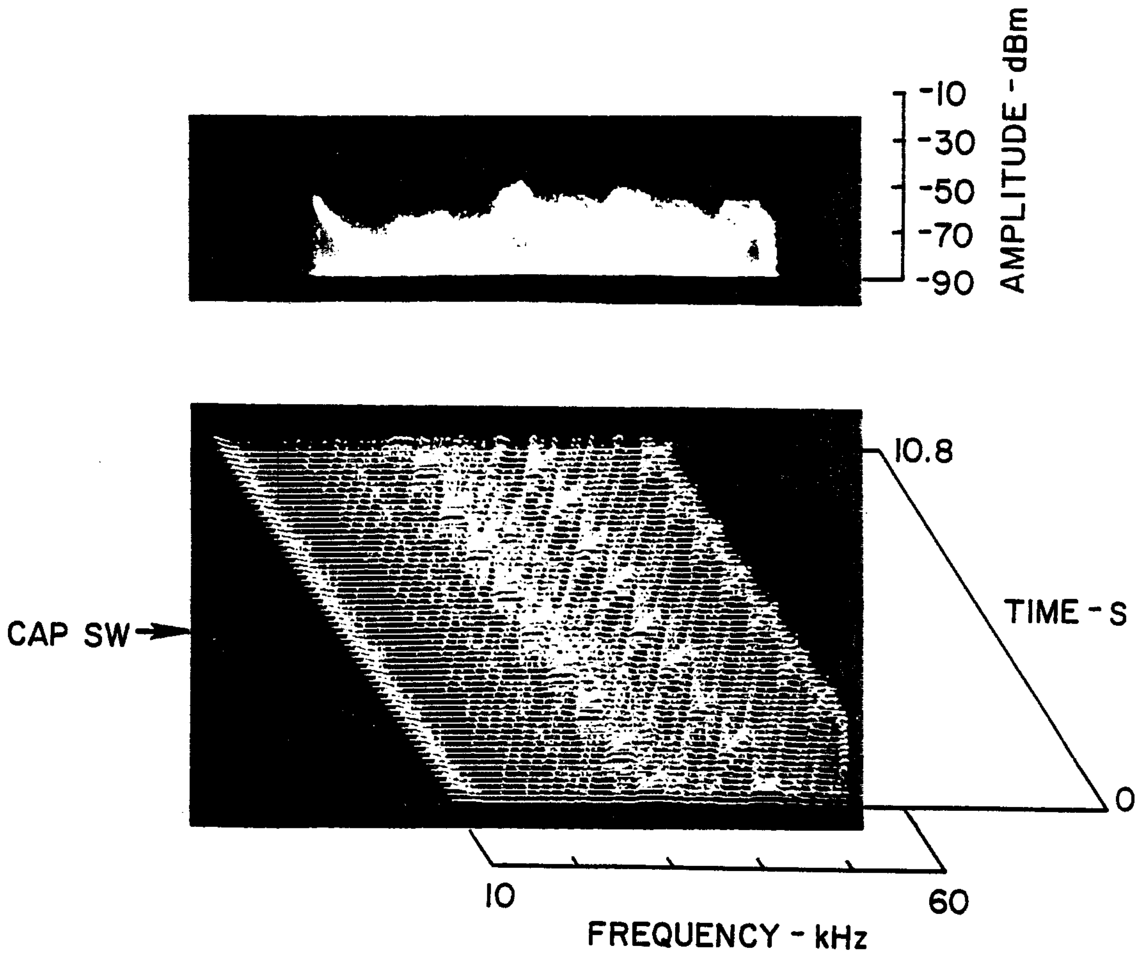

Figure 10 Riser Pole 14111 Site, 10/24/78, 1418